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S-WAVE AND P-WAVE B_c MESON PRODUCTION AT HADRON COLLIDERS BY HEAVY QUARK FRAGMENTATION

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ABSTRACT

We compute model-independently the production rates and transverse momentum spectra for the B_c mesons in various spin-orbital states ($n\,^1S_0$, $n\,^3S_1$, $n\,^1P_1$, and $n\,^3P_J\,(J=0,1,2)$) at hadron colliders via the direct fragmentation of the bottom antiquark and via the Altarelli-Parisi-induced gluon fragmentation. Since all the radially and orbitally excited states below the BD flavor threshold will decay, either electromagnetically, hadronically, or a combination of both, into the pseudoscalar ground state $1\,^1S_0$, they all contribute significantly to the inclusive B_c meson production.

The next and the last family of B mesons to be observed will be the $B_c(\bar{b}c)$ made up of one charm quark and one bottom antiquark. Like the J/ψ and Υ quarkonia, dynamical properties of B_c can be predicted reliably by using perturbative QCD, in contrast to the heavy-light mesons. In the limit $m_c/m_b \to 0$, the B_c system enables us to test the heavy quark symmetry and to understand the next-to-leading terms in the heavy quark effective theory in the applications to the heavy-light B mesons. In addition, the production rates for different spin-orbital states also help us to understand the spin symmetry breaking effects. Phenomenologically, B_c mesons can be used to analyze the mixing of the $B_s^0 - \overline{B_s^0}$ without ambiguity by tagging the charge of the lepton in the decay $B_c^+ \to B_s^0 + \ell^+\nu$ or $B_c^- \to \overline{B_s^0} + \ell^-\bar{\nu}$

Calculations on the production of B_c mesons at e^+e^- colliders were previously performed. But the calculation for the production at hadronic colliders is rather tedious until Braaten and Yuan[1] pointed out that the heavy quarkonium production at the large transverse momentum region is dominated by heavy quark fragmentation. The fragmentation of a heavy quark into a heavy-heavy-quark bound state essentially involves the creation of a heavy quark-antiquark pair, which tells us that the process

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should be hard enough to be calculable in perturbative QCD (PQCD). Explicit calculation of the production rates and the transverse momentum spectra was performed in Ref.,[2] which was based on the direct $\bar{b}$ antiquark fragmentation functions $D_{\bar{b}\to B_c}(z)$ and $D_{\bar{b}\to B_c^*}(z)$ calculated in Ref.[3] It was found[4] that the Altarelli-Parisi-induced gluon fragmentation $g \to B_c$ also contribute significantly to the total production. Since the P-wave fragmentation functions have just been completed,[5] it is natural to include all the S-wave and P-wave contributions to calculate the inclusive production rate.

The direct $\bar{b} \to B_c$ fragmentation function and the induced $g \to B_c$ fragmentation function are coupled by the following Altarelli-Parisi equations:

$$\mu\frac{\partial}{\partial\mu} D_{\bar{b}\to B_c}(z,\mu) = \int_z^1 \frac{dy}{y} P_{\bar{b}\to\bar{b}}(z/y,\mu)\; D_{\bar{b}\to B_c}(y,\mu) + \int_z^1 \frac{dy}{y} P_{\bar{b}\to g}(z/y,\mu)\; D_{g\to B_c}(y,\mu)\,, \tag{1}$$

$$\mu\frac{\partial}{\partial\mu} D_{g\to B_c}(z,\mu) = \int_z^1 \frac{dy}{y} P_{g\to\bar{b}}(z/y,\mu)\; D_{\bar{b}\to B_c}(y,\mu) + \int_z^1 \frac{dy}{y} P_{g\to g}(z/y,\mu)\; D_{g\to B_c}(y,\mu)\,. \tag{2}$$

where $P_{i\to j}$ can be approximated by the usual massless Altarelli-Parisi splitting functions. Similar equations can be written down for the ${}^3S_1$, ${}^1P_1$, and ${}^3P_J$ $(J = 0, 1, 2)$ states. The boundary conditions for the coupled equations are $D_{g\to B_c}(z,\mu) = 0$ for $\mu \le 2(m_b + m_c)$ and $D_{\bar{b}\to B_c}(z, \mu_0 = m_b + 2m_c)$, which is the heavy quark fragmentation function calculated to the order of α_s^2 at the initial scale μ_0 by PQCD. Expressions for the initial fragmentation functions in S-wave states can be found in Ref.[3] and those for P-wave states can be found in Ref.[5]

Numerically integrating the coupled equations with the above boundary conditions, we obtain the direct $\bar{b}$ antiquark fragmentation functions and the induced gluon fragmentation functions for the S-wave and P-wave states at any arbitrary scale $\mu \ge \mu_0$. The inputs to these fragmentation functions are the quark masses m_b and m_c and the nonperturbative parameters associated with the wavefunction of the bound state. These nonperturbative parameters can be calculated within the framework of the potential models.[6] For the two S-wave states there is only one nonperturbative parameter, which is the radial wavefunction $R(0)$ at the origin. The P-wave fragmentation functions have two nonperturbative parameters associated with the color-singlet and color-octet mechanisms. Two of the P-wave states (${}^1P_1$ and ${}^3P_1$) mix to form two physical states because they have the same quantum numbers. The two physical states are denoted by $|1+\rangle$ and $|1+'\rangle$. The mixing and further details can be found in Ref.[5]

The calculation of B_c meson production is simplified by factorizing the whole process into a short-distance process of producing the heavy quark and a long-distance process, which is the fragmentation of the heavy quark into the B_c meson. The differential cross-section for the B_c meson in the ${}^1S_0$ state is given by

$$\begin{aligned} d\sigma\left(B_c(p_T)\right) &= \sum_{ij}\int f_{i/p}(x_1,\mu) f_{j/p}(x_2,\mu)\;\Big[d\hat{\sigma}(ij\to\bar{b}(p_T/z)X,\,\mu)\; D_{\bar{b}\to B_c}(z,\,\mu) \\ &\qquad + d\hat{\sigma}(ij\to g(p_T/z)X,\,\mu)\; D_{g\to B_c}(z,\,\mu)\Big]\,, \end{aligned} \tag{3}$$

where i, j denote all the possible initial partons. The first term in the square bracket is the direct $\bar{b}$ fragmentation contribution and the second term is the induced gluon

Fig. 1. The differential cross sections $d\sigma/dp_T(B_c)$ versus the transverse momentum $p_T(B_c)$ of the B_c meson for different spin-orbital states at the Tevatron.

fragmentation contribution. Similar expressions can be written down for the ${}^3S_1$ and the P-wave states. In the above equation, the factorization scale μ is chosen to be of the order of p_T/z to avoid large logarithms in $d\hat{\sigma}$, while the large logarithms in $D(z)$ can be summed up by evolving the $D(z)$ according to the coupled equations in Eqs. (1) and (2).

In our calculation the factorization scale μ in Eq. (3) is chosen to be

$$\mu = \sqrt{p^2_{T_{\bar{b},g}} + m_b^2}\ , \tag{4}$$

where $p_{T_{\bar{b},g}}$ is the transverse momentum of the fragmentating parton. $p_{T_{\bar{b},g}}$ is related to $p_T(B_c)$ by $p_{T_{\bar{b},g}} = p_T(B_c)/z$. This scale is also used for the parton distributions and the running coupling constant α_s. Explicitly, we used $m_b = 4.9$ GeV, $m_c = 1.5$ GeV, and CTEQ2[7] for the parton distributions. The $\alpha_s(Q)$ is evaluated at 1-loop by evolving from the experimental value $\alpha_s(m_Z) = 0.118$ by $\alpha_s(Q) = \alpha_s(m_Z)/(1 + ((33 - 2n_f)/6\pi)\alpha_s(m_Z)\log(Q/m_Z))$, where n_f is the number of active flavors at the scale Q. We included $gg \to b\bar{b}$, $g\bar{b} \to g\bar{b}$, and $q\bar{q} \to b\bar{b}$ as the hard subprocesses for the inclusive $\bar{b}$ production, and $gg \to gg$, $gq(\bar{q}) \to gq(\bar{q})$, and $q\bar{q} \to gg$ for the inclusive g production. The fragmentation functions at the scale μ are obtained by solving Eqs. (1) and (2) with the boundary conditions mentioned above.

The transverse momentum spectra for different spin-orbital states are shown in

Table 1. The integrated cross sections in pb for the B_c mesons in various spin-orbital states, with the acceptance cuts in Eq. (5), at the Tevatron. $|1+\rangle$ and $|1+'\rangle$ are the two physical P-wave states resulted from the mixing of the $^1P_1$ and $^3P_1$ states.

	$n = 1$	$n = 2$
$^1S_0$	210	130
$^3S_1$	350	210
$^3P_0$	17	24
$^3P_2$	38	54
$\|1+\rangle$	31	29
$\|1+'\rangle$	28	54

Fig. 1, in which the contributions from the direct $\bar{b}$ fragmentation and the induced gluon fragmentation have been added, with the acceptance cuts

$$p_T(B_c) > 10 \text{ GeV} \qquad \text{and} \qquad |y(B_c)| < 1 \tag{5}$$

on the B_c mesons. The curves in Fig. 1 are for $n = 1$ states. The radially excited $n = 2$ states can be calculated similarly with the corresponding nonperturbative parameters. We present the integrated cross sections for $n = 1$ and $n = 2$ states in Table 1.

Since the annihilation channel for the decay of the excited B_c meson states is highly suppressed relative to the electromagnetic and hadronic transitions, all the excited states below the BD threshold will decay into the ground states by emitting photons or pions. Thus, they all contribute to the inclusive production. Adding all the contributions shown in Table 1, we have a total cross section of 1.2 nb, which implies about 1.2×10^5 B_c mesons for 100 pb^{-1} at the Tevatron. This number should almost represent the total inclusive rate, except for a small contribution from the D-wave states.

Thus, we have presented the so far most complete B_c meson production via heavy quark fragmentation, including S-wave and P-wave contributions, at the Tevatron. The B_c meson can be detected via the decays into $J/\psi + X$, in which the J/ψ is fully reconstructed by the leptonic decay. If X is a charged lepton, then the event has a very distinct signature of three charged leptons coming out from the same displaced vertex. If X can be fully reconstructed, together with the reconstructed J/ψ the B_c meson can be fully reconstructed.

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